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Weight Determination of Stockpiled Ferrochrome Using Microgravity Measurements

by Keith J. Sjostrom, Thomas E. Berry

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Weight Determination of Stockpiled Ferrochrome Using Microgravity Measurements

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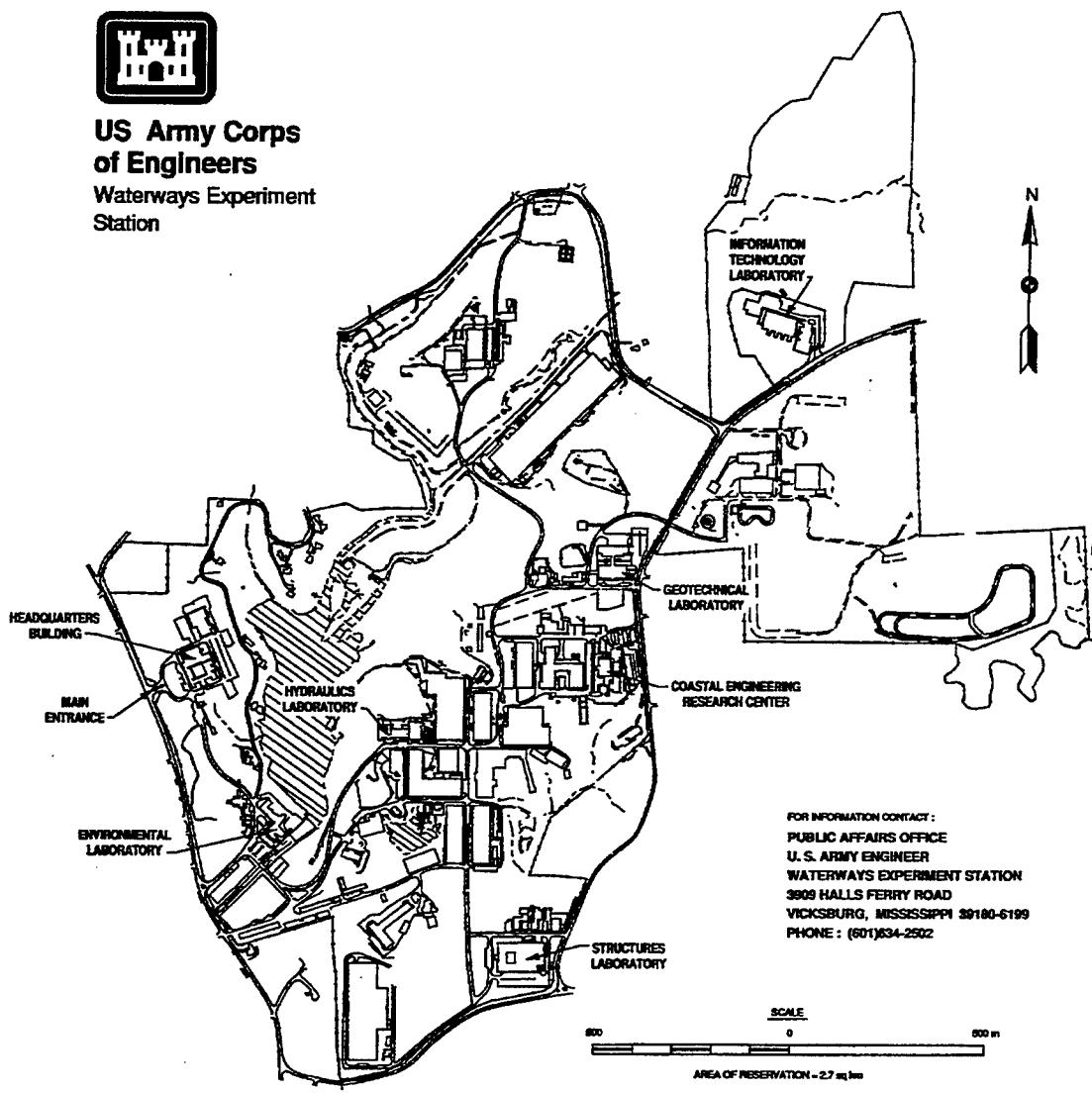
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Preface

A geophysical investigation to determine the material density and overall weight of three stockpiles of high carbon ferrochrome was conducted at an industrial site in Charleston, SC, by personnel of the Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL), and Natural Resources Division (NRD), Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES). Analysis of microgravity measurements collected along traverses established across each ore pile provide representative bulk density values of the processed ore. The weight for each pile is computed by multiplying the material density values and measured ore pile volumes. Microgravity and topographic measurements were collected at the site during the period 24-28 June 1996. The study was performed under sponsorship of the Defense National Stockpile Center (DNSC) of the Defense Logistics Agency. The DNSC Project Coordinators were Mr. G. A. Vanegas and Ms. Judy Munday.

The overall test program was conducted under the general supervision of Drs. W. F. Marcuson III, Director, GL, and A. G. Franklin, Chief, EEGD, and Drs. John W. Keeley, Director, EL, and Robert M. Engler, Chief, NRD. Mr. Keith J. Sjostrom was the principal investigator. This report was prepared by Messrs. Sjostrom and Thomas E. Berry under the supervision of Mr. J. R. Curro, Jr., Chief, Engineering Geophysics Branch, EEGD, GL, and Mr. H. W. West, Chief, Environmental Characterization Branch, NRD, EL, respectively. Data acquisition and analysis support was provided by Ms. Evelyn Villanueva and Mr. Rodney L. Leist, EEGD, GL. Volume calculation support was provided by Mr. Jerry E. Ballard, NRD, EL. Assistance in report preparation was provided by Ms. Lori M. Davis, EEGD, GL. Graphical presentation of the ore piles was provided Mr. Grady A. Holley, Applied Research Associates, Vicksburg, MS.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
pounds	0.45359	kilograms
tons	907.1847	kilograms
cubic feet	0.02832	cubic meters
pounds per cubic foot	0.01602	grams per cubic centimeter
pounds per cubic foot	16.0184	kilograms per cubic meter
miles (U.S. statute)	1.6093	kilometers
Gal (measure of gravity)	1.0	centimeter per second squared
Gal (measure of gravity)	0.01	meter per second squared
microGal	1.0×10^{-8}	meter per second squared

1 Introduction

Background

The Defense National Stockpile Center (DNSC) of the Defense Logistics Agency maintains stockpiles of high-grade ores at various locations throughout the country. Three such stockpiles of high carbon ferrochrome are located at an industrial complex operated by the Macalloy Corporation in Charleston, South Carolina (see Figure 1). The ore piles to be studied are spatially oriented as illustrated in Figure 2 and designated as Piles Nos. 2, 4, and 6. The pile designations, material types, dimensions, and originally reported gross weights, as provided by DNSC, are listed in Table 1. DNSC requested assistance from the U.S. Army Engineer Waterways Experiment Station (WES) to determine the bulk material density and overall pile weight for each of the three ore piles. The ferrochrome material in each pile ranges in size from fine-grained particles to cobbles.

While the initial or as-placed weight of each ferrochrome pile is known or has been estimated in previous years, the measures or estimates may not be reliable. DNSC has a requirement from the Inspector General's Office to produce current weight estimates as part of an internal audit. The audit stems from discrepancies between DNSC and Macalloy Corporation concerning the weight on record and the as-placed weight of the stockpiled ferrochrome material. The reliability of the weight estimates are important for assessing the current ferrochrome inventory at the site in order to set a fair market value of the material when the ore stockpiles are sold.

Standard geotechnical methods for bulk density determination are not readily applied to the in-place pile material because of the large range in size of the ferrochrome ore. Measuring the near-surface density of pile materials by a technique such as the ring density test will not give density values representative of the material near the bottoms of the piles. In general, any density determination method which requires displacing materials, which are placed in known volume containers and weighed, are not reliable or representative of the in-place materials.

A method for computing the weight of the in-place ore stockpiles and determining a truly representative bulk density for each pile is to measure the gravitational attraction of the piles. The gravitational attraction of the piles is

the result of the integrated effect of the in-place bulk material density distributed over the volume of the pile. Analysis of the gravitational anomaly recorded over piles of ore results in estimates of the representative bulk density of the ore material. The weight of the ore pile is computed by multiplying the density values and measured pile volumes. Gravitational determination of near-surface densities for use in gravity survey data reductions are done routinely in geophysics. However, determination of densities by gravity surveys is a non-standard technique for the present application and cannot promise the same level of accuracy as laboratory density determination or a precisely controlled geotechnical field density determination.

Purpose and Scope

The objectives of this research program are to determine the bulk density weight of the three ferrochrome stockpiles. Material density values are derived through analysis of microgravity measurements performed over each ore pile. Pile weight is the product of the measured pile volume, determined using standard topographic surveying procedures, and computed material density. The results will be used to check the current ore inventory with previous records as part of an internal audit within DNSC.

2 Principles of Microgravity Surveying

The Microgravity Method

Gravimetry is one of the few geophysical methods to allow determination of the nature and magnitude of subsurface density anomalies. Near-surface density anomalies produce localized variations in the gravitational force field on the surface of the earth. Systematic measurements of the gravitational field with a gravimeter allows the field to be mapped on the surface of the earth. Correcting the measured gravity field for the normal gravitation field of the earth and any large scale gravity effects, relative to the survey area of interest, a gravity anomaly field is left. Analysis of the gravity anomaly field results in estimates of the density contrast between the densities of the anomalous feature and surrounding material and the depth and geometry of the localized feature.

In many cases, analysis of the surface gravity anomaly allows the mass excess or deficiency associated with the density contrast to be determined (Butler 1980; Telford et al. 1990). When the two densities associated with the density contrast and the volume of the feature are known or can be measured, then the actual mass associated with the localized feature can be determined. For cases where a profile of gravity measurements crosses a topographic surface feature such as a hill, ridge, or pile and the surface feature is entirely above some reference datum, it is possible to determine the actual bulk density of the material comprising the structure directly from the gravity measurements (Nettleton, 1940; Parasnis 1979; Telford et al. 1990; Sjostrom and Butler 1996). It is this last capability that is used in the ore pile investigations.

Microgravimetry refers to high-resolution surveys of the gravitational field with gravimeters that have measurement sensitivity and accuracy of approximately 1 microgal ($1 \mu\text{Gal}$). Since the normal earth's gravitational field on the surface is approximately 1,000 Gal, microgravimetry involves measurements of gravity with precision and accuracy 10^{-9} times that of the normal earth's gravitational field. The microgravity measurements recorded for this study were completed using a LaCoste and Romberg Model D Gravimeter as shown in Figure 3. The measurement characteristics of gravimeters used for

microgravity surveys are discussed in detail in Butler (1980) and Torge (1989).

Microgravimetric surveys are of two types: (a) profile surveys, where gravity measurements are made along traverses generally perpendicular to the presumed strike of a linear-type structure, such as a fault, ridge, valley, buried river channel, or an elongated pile of material on the surface; and (b) areal surveys, where gravity measurements are made at stations on a grid over an area. Microgravity surveys are often conducted with measurement points separated by 5 to 30 ft to enhance the detectability and resolution of small and closely spaced subsurface features. Station locations and relative elevations must be accurately determined by a site leveling survey in which the station locations and elevations are measured to the nearest 0.1 and 0.01 ft, respectively. The field procedures used for the surveys are dictated by considerations of survey objectives and subsequent corrections which must be made to the measured data. The measurements in a microgravity survey are normally made relative to a local reference station, and there is usually no attempt to tie the values to an absolute gravity determination.

Field Procedures

Gravity values are collected along traverses established across the base, side slopes, and tops of each ore stockpile. The gravity survey lines must be established and measured using microgravimetric procedures such as those outlined in Butler (1980). For piles that are elongated in one direction, the profile lines are oriented approximately perpendicular to the long axis or strike of the ore pile with three or four profiles crossing each pile depending on the pile dimensions. Each survey line consists of approximately 19 to 21 measurement stations much like the one shown in Figure 4. The measurement stations are located so that at least four stations are positioned on either side of and off the pile on the non-ore base material to provide background gravity readings necessary for data analysis. The remaining 11 to 13 stations are located on the side slopes and tops of the ore piles as shown in Figure 5. These are the measurement stations from which the gravity anomaly is determined and material densities derived. Typically, three measurement stations are located on each side slope with the remainder positioned on top of the pile. Horizontal spacing between stations varies from 5 to 20 ft depending on the number of gravity stations and overall dimensions of the piles. Horizontal locations (x, y coordinates) and elevations (z coordinate) are established by electronic surveying instruments using standard topographic surveying procedures. Horizontal positions are measured to an accuracy of 0.1 ft and elevations are determined to an accuracy of 0.01 ft using mean sea level as a reference elevation. In addition to the position surveying performed for establishing the gravity survey lines, position measurements are also acquired for use in determining pile volumes. Further details regarding the position surveying procedures are presented in the next chapter.

Each gravity profile line has a base station located off the pile at the 'start' of the survey line. All elevations and gravity measurements along the line are referenced to the base station elevation and base station gravity measurement. The gravity measurements along each profile line are typically determined in two measurement programs. Following the initial gravity readings at the base station, the first measurement program consists of approximately 10 measurements as the survey proceeds towards and up the slope (see Figure 6) of the ore pile, stopping at a measurement station that is located midway along the traverse near the crest of the stockpile; often the highest elevation along the profile. Once the reading at the top of the pile is collected, the gravity survey loops back to the base station for additional readings to conclude the first program. The second measurement program for the profile line starts at the opposite end of the line from the base station and proceeds up the 'back' side of the ore pile. Gravity readings are collected until the midway point along the survey line is reached. This station is the same stopping point as used for the first program. After recording the gravity meter reading, the survey again loops back to the base station for the third and final set of readings. This two program procedure results in three measurements at the base station and two readings at the central measurement point of the line.

The multiple base station measurements are used for the earth tide and instrument drift corrections and data quality control. Since measurements at the base station are used as the reference data for the survey line and for correcting all other gravity measurements along the line, special care is exercised in acquiring data at the base station (Butler 1980). The two measurements at the central measurement point are also used for survey quality control. Equipment performance and time constraints are also applied to each data acquisition program. If any type of equipment problem, such as jarring the instrument or low battery output, occurs during a program, the entire program is repeated. If the total program time exceeds 60 minutes, the survey line is divided into three programs. However, programs are typically completed in less than 60 minutes. Also, if the data quality and multiple readings are not within set limits (Butler 1980), the survey program may also have to be rerun.

Gravity Data Corrections

Corrections to microgravity data are required in order to compensate for normal gravity variations at the site over the time span required for the survey. Measured values are reduced in such a manner as to imply that all gravity data are collected along the same reference datum by implementing gravity corrections for the effects due to latitude, elevation, topography, earth tides, and instrument drift. In this manner, variations in the corrected gravity values are assumed to be caused by the stockpiles of processed ore. The normal gravity variations and compensating corrections applied to micro-gravity data are discussed in brief below. For a more in depth discussion of gravity data corrections, please refer to Butler (1980), Telford et al. (1990), or Sjostrom and Butler (1996).

Corrections for time variations (drift). Gravity values over the survey area change with time because of earth tides and instrument drift. Earth tides, like ocean tides, are caused by the orientation of the sun and moon and are of sufficient amplitude to be detected by sensitive gravity meters. Instrument drift is caused by creep of the metal components in the meter due to thermal expansion or excessive movement. Over short time periods (less than 60 min), drift due to tidal and instrument fluctuation can be assumed to be linear over time. The usual procedure for correcting for drift is to reoccupy a base station frequently and assume that the gravity values at all stations in the survey area vary in the same manner as those between readings at the base station. Differences in gravity values at the base station are plotted with respect to time to produce a drift curve. The drift correction, denoted as Δg_{zD} , for each station is determined directly from the graph. Positive drift requires a negative correction and vice-versa.

Latitude correction. Both the rotation of the earth and its non-spherical shape produce an increase in gravity values with latitude. For microgravity surveys, it is usually sufficient to assign a reference latitude to the base station and use Equation 1 to compute latitude corrections for all other stations. The latitude correction, denoted as Δg_{zL} , is:

$$\Delta g_{zL} = \pm \left(0.2471 * \sin(2\phi) \frac{\mu Gal}{ft} \right) * \Delta s \quad (1)$$

where Δs is the north-south distance (in feet) between the measurement and base station and ϕ is the reference latitude of the base station. The correction term is added to the measured gravity value if the station is positioned south of the base station and subtracted if located north of the base station.

Free air correction. The free air correction, denoted as Δg_{zFA} , compensates for variations in gravitational attraction caused by the changing distances of the measurement stations from the center of the earth. The free air correction formula is:

$$\Delta g_{zFA} = \pm 94.041 \frac{\mu Gal}{ft} * \Delta h \quad (2)$$

where Δh is the difference in elevation (in feet) between the measurement station and reference elevation of the base station. The correction is added to the measured gravity value if the station is higher in elevation than the reference elevation, and vice versa.

Bouguer correction. The Bouguer correction compensates gravity values affected by differing masses of material beneath the measurement stations caused by elevation variations. The ore material between the reference elevation of the base station and the elevation of a measurement station is approximated by an infinite horizontal slab with density equal to that of the material beneath the station. The correction, denoted as Δg_{zB} , is calculated using the Bouguer slab formula:

$$\Delta g_{zB} = \pm \left(12.774 * \rho \frac{\mu Gal}{ft} \right) * \Delta h \quad (3)$$

where ρ is the material density (in g/cm^3) and Δh is the elevation difference (in feet) between the measurement and base station. The quantity Δg_{zB} is subtracted from the measured gravity if the station is above the reference elevation, and vice versa.

When all of the preceding corrections have been applied to the observed gravity data, the result is the Bouguer gravity value, denoted as g_B . The Bouguer gravity value at a measurement station is given by

$$g_B = g_{obs} \pm \Delta g_{zL} \pm \Delta g_{zFA} \pm \Delta g_{zB} \pm \Delta g_{zD} \quad (4)$$

where g_{obs} is the observed gravity reading and the remaining terms are the gravity corrections discussed above. Subtracting the gravity readings recorded at the base station, denoted as g_{base} , from the Bouguer gravity values at each station using the equation

$$\Delta g_B = g_B - g_{base} \quad (5)$$

results in the Bouguer gravity anomaly. The Bouguer gravity anomaly is used in determining the density of the ore pile material whether through direct calculation or gravity modeling algorithms.

Determination of Bulk Material Density

In standard gravity surveying to determine geologic structure, the Bouguer corrections in the reduction of gravity data require a knowledge of the average densities of the near-surface rock and sediments. In the application of using gravity measurements to estimate the surface and subsurface densities of earth materials, such as in the scope of this project, two methods were used to estimate the density of the stockpiled ferrochrome. The first method, developed by Nettleton (1940), is an indirect, graphical technique to determine density. A plot of the observed gravity values that have undergone the drift, latitude, and free air corrections versus distance along the survey line is, at this point, strongly correlated to the shape of the measured topography over the pile. Applying the Bouguer correction numerous times over a range of material density values, the resultant gravity anomaly curve that has the least correlation with the topography curve, ideally a correlation factor of zero, is considered to be the most nearly correct bulk density value for the ore pile material. An example of this application is illustrated in Figure 7. This method has the advantage of averaging the effect of density variations more accurately than can be done from surface or core samples (Dobrin 1976). This method works best when the near-surface material is relatively homogeneous in nature.

The second method is an analytical approach developed by Parasnis (1979) and similar to Nettleton's graphical method. Expanding Equation 5 to include the observed gravity readings and all of the gravity correction terms, we obtain the equation

$$0 = [g_{obs} - g_{base} + (\pm \Delta g_{zD} \pm \Delta g_{zL} \pm \Delta g_{zFA}) \pm \Delta g_{zB}] - \Delta g_B \quad (6)$$

Further expansion of the Bouguer slab correction term Δg_{zB} in Equation 6 and subsequent algebra solving for the material density parameter ρ , we get

$$\rho = \frac{g_{obs} - g_{base} + (\pm \Delta g_{zD} \pm \Delta g_{zL} \pm \Delta g_{zFA})}{12.774 * \Delta h} - \frac{\Delta g_B}{12.774 * \Delta h} \quad (7)$$

where ρ is defined in terms of g/cm^3 . For a single, straight line gravity traverse over a survey area, Equation 7 resembles the formula for a straight line; i.e. $y = mx - b$. To solve for an average bulk density value, Parasnis considers the Bouguer gravity anomaly, defined in Equation 5, to be a random error with a mean value equal to zero (Telford et al. 1990). Therefore, plotting the values in the numerator versus the values in the denominator of the first term and drawing the best fit straight line through the data points and through the origin, the absolute value of the slope will be the material density ρ . Obviously, as Telford (1990) points out, all the points will not lie on this line unless the subsurface is uniform and the Bouguer anomaly Δg_B is everywhere zero. Therefore, the best fit straight line through the data is found using least squares analysis. An example of Parasnis's method is presented in Figure 8.

Depending on the dimensions of each ore pile, three or four gravity surveys are performed to determine the average bulk density of the ore material using either Nettleton's or Parasnis' method. The three or four survey lines conducted over an ore pile results in the determination of the same number of spatially distributed, volume-averaged bulk density values for each pile. The bulk density values are averaged to determine a single in-place density value for the ore pile material.

3 Data Analysis and Results

Determination of Ore Pile Volume

Topographic surveys to compute the volumes of the ore stockpiles were completed using standard land surveying methods. Topographic field data were acquired using a Wild GRE4 data collector and T-1000 theodolite with a DI3000 laser rangefinder. A Trimble 4000-SSE Global Positioning System (GPS) RTK System and a TDC1 data collector were also used to establish six control points at the site and conduct a portion of the topographic survey. Horizontal data were referenced to the 1927 North American Datum (NAD) South Carolina State Plane coordinate system and the vertical data are referenced to USGS Bench Mark V-70 at the site. The elevation of the bench mark is 17.854 ft Mean Sea Level (MSL).

The limits of the topographic survey program are determined by the location of the gravity measurement stations on and off the ore pile. This program includes surveying each ore pile from toe to toe while taking into account all ridges, depressions, and other significant characteristics on the pile surface. A total of 1,463 elevation points were obtained over the three piles during the survey. The base of each stockpile is determined by a planar surface passing through the elevation points along the toe of the pile. *It should be noted that any ore material below the planar surface caused by material settlement underneath the pile is not included in the pile volume determination and, hence, the ore stockpile weight.*

The acquired elevation data are analyzed using both two- and three-dimensional (2-D, 3-D) maps developed in Arc-Info. The 2-D contour plots illustrate the elevation of distinct features unique to each pile. The contour interval is one foot. Volumes were computed using the 3-D surface models of each ore pile. The surface models are designed into a Triangular Irregular Network (TIN), also using Arc-Info, and interpolated into regular grid networks using a grid interval of 0.5 ft. The volume estimates for each grid section are computed between the 3-D surface model and planar base of a pile. Grid volumes are accumulated to provide a total reported volume, in units of cubic feet (ft^3), for each pile. The average volume of each pile is noted on the contour plots, listed in Table 2, and used in the weight calculation of ore material.

Calculation of Material Density

Depending on the long axis dimension of each ore pile, three or four gravity surveys are performed to determine the average bulk density of the ferrochrome ore. The observed gravity data acquired along each profile are analyzed using Equation 8 and applying Parasnus' Method to compute a density value over an individual survey line. Nettleton's Method, an indirect, graphical technique to determine density, was also used to verify results. The bulk density values are averaged to determine a single in-place density value for the ferrochrome material. Standard deviation values are also computed to reflect the confidence interval of the results.

Calculation of Ore Pile Weight

Following determination of representative material density values from the microgravimetric measurements, the total weight of the ore pile material is calculated by incorporating the volume estimates of each respective ore pile. The computed weight of the ferrochrome stockpile is computed using the equation

$$Weight = (\rho) * \left(62.428 \frac{lb}{ft^3} \right) * (V) \quad (8)$$

where ρ is the computed density of the ferrochrome (in g/cm³) and V is the calculated volume of the ore pile (in ft³) above the ground surface. The total weight is given in units of pounds (lbs). A possible error range of the ore pile weight is computed by multiplying the standard deviation of the density values and the respective volume of the stockpile.

The difference between the originally reported weight of the ferrochrome stockpiles and the calculated weight is given in terms of percent using the equation

$$Difference = \left(\frac{Calculated - Reported}{Reported} \right) * 100\% \quad (9)$$

where 'Calculated' and 'Reported' are the respective pile weights in units of pounds (lbs). In the discussion of the results, negative percent differences represent calculated pile weights that are less than the reported gross weights.

Results

Three piles of stockpiled ferrochrome were studied at the Macalloy Corporation industrial complex in Charleston, SC. The pile descriptions,

dimensions, and reported weights as provided by the DNSC are listed in Table 1. The averaged bulk density value for each pile multiplied by the respective ore pile volume to determine the total weight of the stockpiled ferrochrome. The measured volumes, average bulk density values, and computed weights for each pile are presented in Table 2. The differences between the computed weight and the weight on record for Piles Nos. 2, 4, and 6 are listed in Table 3. The results of the investigation for each pile, listed in numerical order, are described below.

Pile No. 2: Ferrochrome. Pile No. 2, as shown in Figure 9, consists of 38,501,740 lbs of domestic, high carbon ferrochrome as documented by DNSC. Some time prior to the gravimetric investigation, approximately one half of the southern portion of the pile had been removed. However, removal of the ferrochrome material exposed the fact that the ground beneath the ore pile had settled approximately two feet even though the material is situated on an asphalt pad. Settlement of the ground beneath the pile is further enhanced by the ponded water along the toe of the southern slope as shown in Figure 9. Three gravity survey lines were performed over the pile as indicated in the elevation contour plot of Pile No. 2 shown in Figure 10. Each survey line had 11 gravity stations located on the ferrochrome material. Computed density values derived using the gravity data analysis procedures range from 3.483 to 3.877 g/cm³ (217.4 to 242.0 lb/ft³). The average material bulk density is 3.683 g/cm³ (229.9 lb/ft³) with a standard deviation of 6.08 percent or 0.224 g/cm³ (14.0 lb/ft³). The average volume of the ferrochrome stockpile is estimated at 161,602.4 ft³. Using the computed averages for the material density and pile volume (see Table 2), the estimated total weight of Pile No. 2 is 37,155,999.4 lbs. The difference between the computed weight in relation to the weight on record (see Table 3) is approximately -3.50 percent. The estimated weight range as derived from the standard deviation of the material density is 2,259,827.2 lbs.

Pile No. 4: Ferrochrome. Pile No. 4 is the largest ore pile surveyed and the material is described as domestic, high carbon ferrochrome. The reported weight is 138,560,620 lbs as listed in Table 1. A photograph of the southwestern corner of Pile No. 4 is shown in Figure 11 and an elevation contour plot is illustrated in Figure 12. The ferrochrome material is situated on a concrete pad and no indications of settlement were visible. The estimated pile volume is 570,222.1 ft³. Four gravity surveys were performed over the pile (see Figure 12) with 13 of the 20 gravity stations comprising each survey line positioned on the ore material. Computed density values derived using Parasnus' Method range from 3.443 to 3.999 g/cm³ (214.9 to 249.6 lb/ft³) with an average value of 3.775 g/cm³ (235.6 lb/ft³). The estimated weight of Pile No. 4 as determined by multiplying the average density and pile volume is 134,381,790.4 lbs as indicated in Table 2. The standard deviation of the average computed density is 0.213 g/cm³ (13.3 lb/ft³) which corresponds to an error bound on the weight estimate of 7,582,336.8 lbs. This error bound is 5.64 percent of the computed ore pile weight. The computed weight of the ferrochrome varies from the reported gross weight by -3.01 percent.

Pile No. 6: Ferrochrome. Pile No. 6 is an irregular shaped pile of domestic, high carbon ferrochrome situated on an asphalt surface and is the smallest pile of the three piles surveyed. A photograph taken towards the southwest at Pile No. 6 is presented in Figure 13 and an elevation contour plot of the ore pile is illustrated in Figure 14. The ferrochrome stockpile has an estimated volume of 39,671.3 ft³. Three gravity surveys were performed over the width of the pile (see Figure 14) with 10 to 11 gravity stations positioned on the ore material. Analysis of the corrected gravity data result in material density values varying from 3.017 to 3.144 g/cm³ (188.3 to 196.3 lb/ft³). The average computed density of the ferrochrome is 3.085 g/cm³ (192.6 lb/ft³) with a standard deviation of 0.069 g/cm³ (4.3 lb/ft³). The estimated weight of Pile No. 6 using the computed density and volume values is 7,640,310.7 lbs with a possible deviation of 170,652.8 lbs. The deviation terms for the material density and pile weight are 2.23 percent of the computed values. The difference between the average calculated pile weight and the reported gross weight, as provided by DNSC, of 7,769,200 lbs is -1.66 percent.

Comparing the computed weights for each ore stockpile to the reported weights provided by DNSC, it is observed that all of the calculated results are less than those on record and within 3.5 percent of the reported value. The percent differences for each pile are well within the 10 to 14 percent range estimated by Sjostrom and Butler (1996) in similar investigations. The less than reported values are reasonable considering the scatter of ore material near the base of some piles, settlement of the ore pile not detected by the topographic or gravity surveys, difficulties in differentiating the true base of each pile, and inhomogeneities within the ore creating highly variable density estimates. The computed average density values and pile weights have standard deviation values ranging from 2.23 to 6.08 percent of the calculated values.

The 3.5 percent discrepancy between the computed and reported stockpile weights for Pile No. 2 is likely caused by difficulties in modeling the base of the stockpile. Settlement of the ground and asphalt pad beneath the ore pile has caused material near the center of the pile to be positioned below the elevation of the original ground surface. Fortunately, since a portion of the pile was removed many years ago, elevation measurements reflecting the amount of settlement could be obtained to better determine the base of Pile No. 2. The 3.01 percent difference between the reported and calculated weights for Pile No. 4 is likely caused in part by inaccuracies in the differentiation of the intricate ridge and furrow geometries on top of the pile.

The small range of values for both the percent standard deviation and percent difference between the computed and measured weights of each ferrochrome stockpile are well below the expected experimental errors and, thereby, are considered accurate estimations of the ore pile weights. In other words, any discrepancies between the weight on record and calculated weight are well within the experimental bounds of the determined weight value. It is also noted that measured or reported weights are sometimes in error as was

documented in Sjostrom and Butler (1996) during a similar study on ore piles at the Sierra Army Depot, CA.

The average computed material densities for Piles Nos. 2, 4, and 6 are 3.683, 3.775, and 3.085 g/cm³, respectively. The lower density value for Pile No. 6, as compared to Piles Nos. 2 and 4, is likely attributed to less fine-grained particles within the stockpile. It is of interest to note that a gravimetrically determined bulk material density value of 3.843 g/cm³ was determined for a stockpile of low carbon ferrochrome at the Ravenna Army Ammunition Plant, OH (Sjostrom and Butler 1996).

4 Conclusions

The Defense National Stockpile Center (DNSC) of the Defense Logistics Agency maintains stockpiles of high-grade ores at various locations throughout the country. Three such stockpiles of domestic, high carbon ferrochrome are located at the Macalloy Corporation industrial complex in Charleston, SC. DNSC has a requirement to produce current weight estimates for each of these piles as part of an internal audit. While the initial, as-delivered weights of the stockpiles are known or have been previously estimated, discrepancies are thought to exist and, therefore, the current reported weights are not considered to be reliable.

Microgravity measurements were performed over each ore pile to provide high-resolution surveys of the gravitational field to determine the average bulk density of the ferrochrome material. Each microgravity survey line, oriented perpendicular to the long axis of the ore pile, consists of approximately 19 to 21 measurement stations. Eleven to 13 of the measurement stations are located on the ore material and it is these stations from which the gravity anomaly is determined and material densities derived. Each survey line has a base station to which all elevations and gravity measurements are referenced. The measured gravity values are corrected to the base station reference datum by implementing the necessary gravity adjustments for the effects caused by latitude, elevation, topography, earth tides, and instrument drift. In this manner, variations in the corrected gravity values are assumed to be only caused by the ore pile material.

Analysis of the gravity anomaly data was completed through the use of Nettleton's and Parasnis' methods. Each of these methods computes, for the three or four survey lines conducted over the ore piles, the same number of spatially distributed, volume-averaged bulk density values for ore pile material. The bulk density values are averaged to determine a single, in-place density value for the ore with computed standard deviations to reflect the confidence interval of the result. These methods have the advantage of averaging the effect of density variations more accurately than can be done from surface or core samples.

Topographic surveys to compute the volumes of the ore stockpiles were completed using standard land surveying methods. The topographic survey program took into account all ridges, depressions, and other significant

characteristics on the surface of the stockpiles. The base of each pile is determined by a two-dimensional surface passing through the elevation points along the toe of the pile. Volumes were computed using Arc-Info software routines from three-dimensional pile representations. It should be noted that any ore material below the planar surface, caused by settlement of the ground beneath the ore pile, may not be included in the pile volume determination and, hence, the ore stockpile weight.

The average calculated weights for each ferrochrome stockpile are 37,155,999.4 lbs, 134,381,790.4 lbs, and 7,640,310.7 lbs for Piles Nos. 2, 4, and 6, respectively. The calculated weights, although slightly less than weight on record, are within 3.5 percent of the reported weights provided by DNSC. The small percent differences are well below the expected experimental errors and, thereby, are considered accurate estimations of the ore pile weights. For the premise of this study, any discrepancies concerning the weight of the in-place ore and documented weight are within the experimental bounds of the geophysical investigation and data analysis procedures. The less than reported values are reasonable considering the scatter of ore material near the base of some piles, settlement of the ore pile not detected by the topographic or gravity surveys, difficulties in differentiating the true base of each pile, and inhomogeneities within the ore creating highly variable density estimates.

Pile No. 2 is the only stockpile in which the ground beneath the ore pile has settled whereby causing the material near the center of the pile to be positioned below the elevation of the original ground surface. Fortunately, since a portion of the pile was removed many years ago, elevation measurements reflecting the amount of settlement could be obtained to better determine the pile base. Taking into account the amount of settlement along the southern toe of the pile, the computed weight for Pile No. 2 is 3.5 percent less than the reported weight. The 3.01 percent difference between the reported and calculated weights for Pile No. 4 is likely caused in part by inaccuracies in the differentiation of the intricate ridge and furrow geometries on top of the pile.

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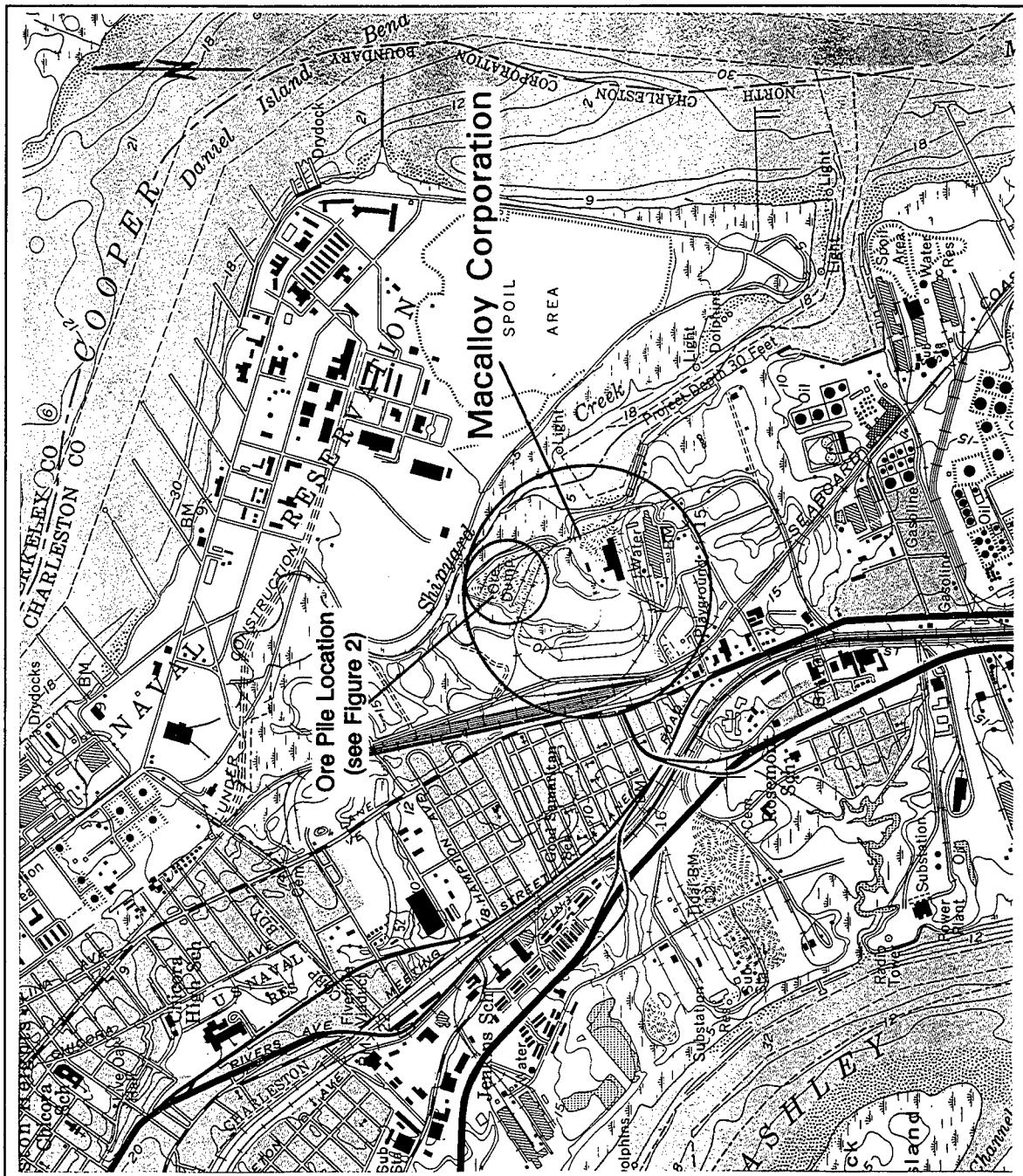


Figure 1. Location of ferrocchrome stockpiles in Charleston, SC

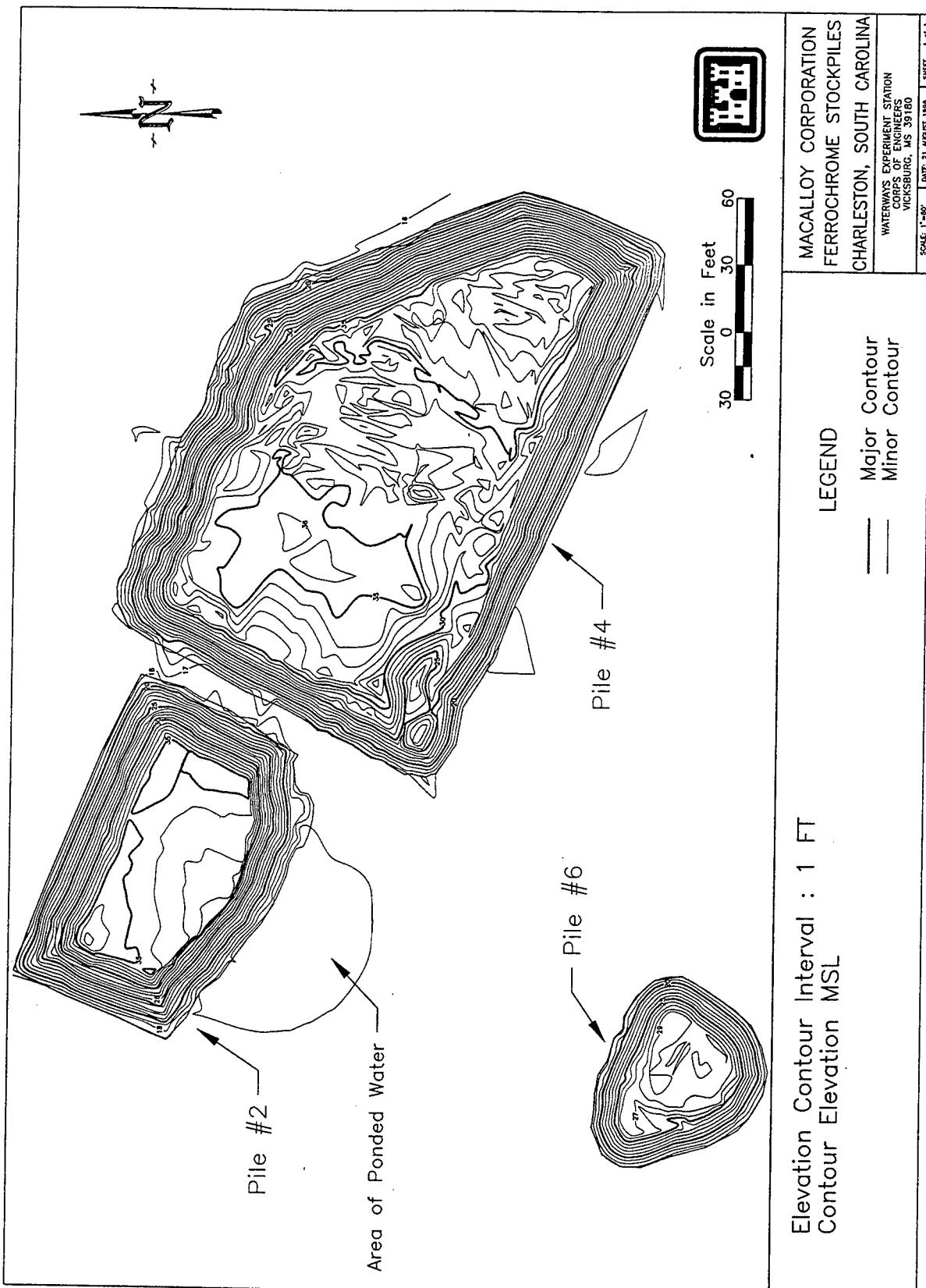


Figure 2. Spatial orientation of the three ferrochrome stockpiles



Figure 3. LaCoste and Romberg Model D gravity meter

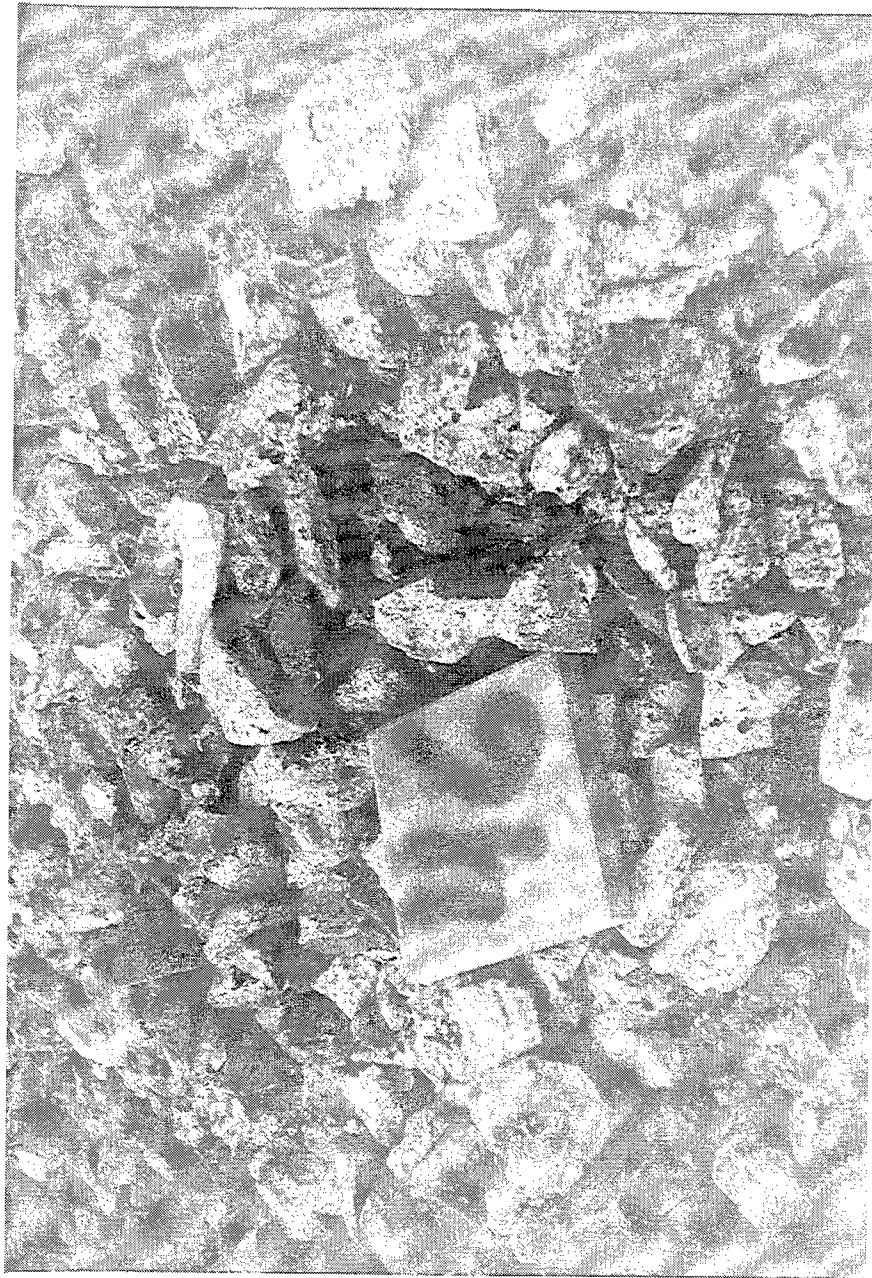


Figure 4. Microgravity measurement station



Figure 5. Microgravity stations positioned on ore pile



Figure 6. Microgravity measurement on side slope of ore pile

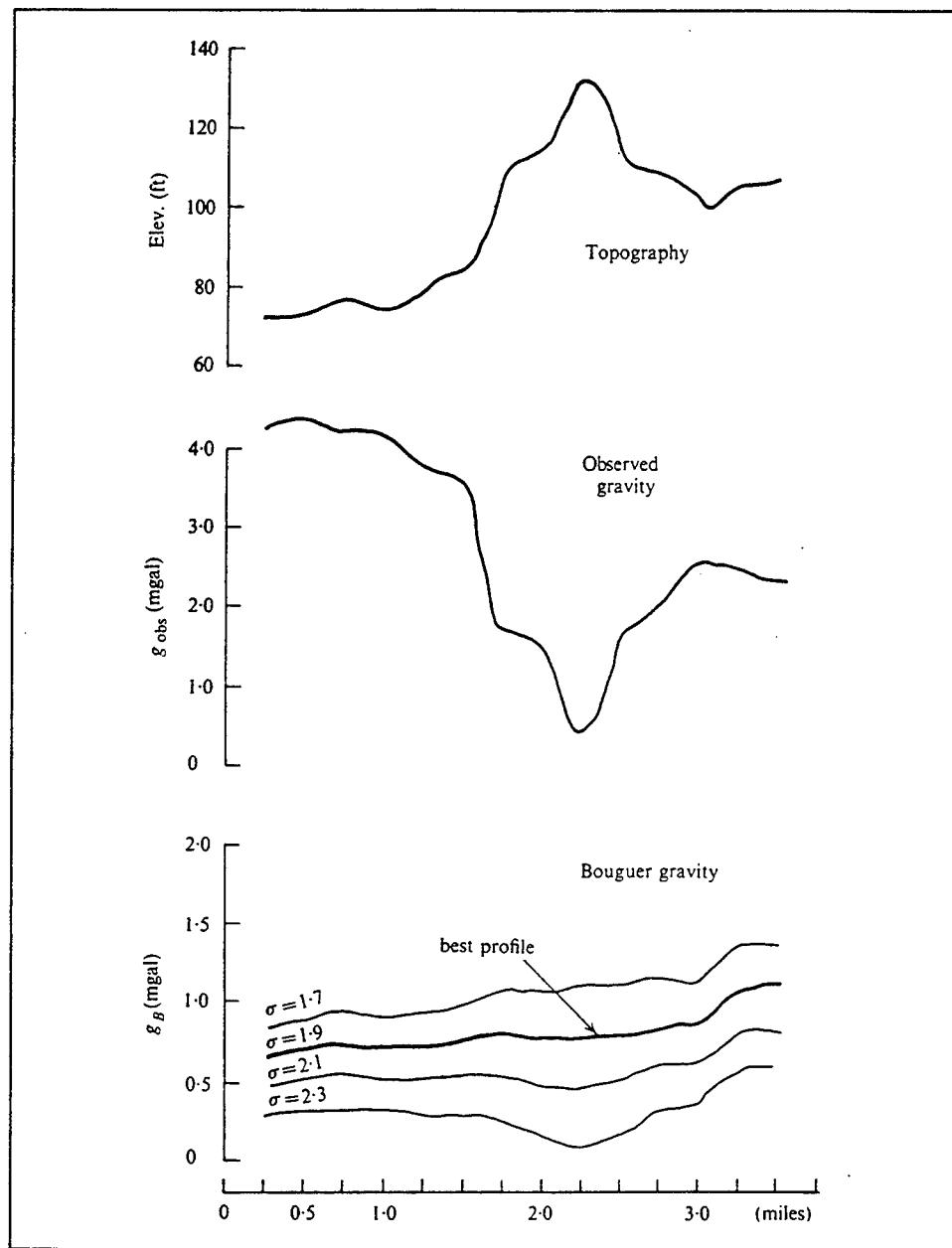


Figure 7. Application of Nettleton's method for estimating material density
(from Telford et al. 1990)

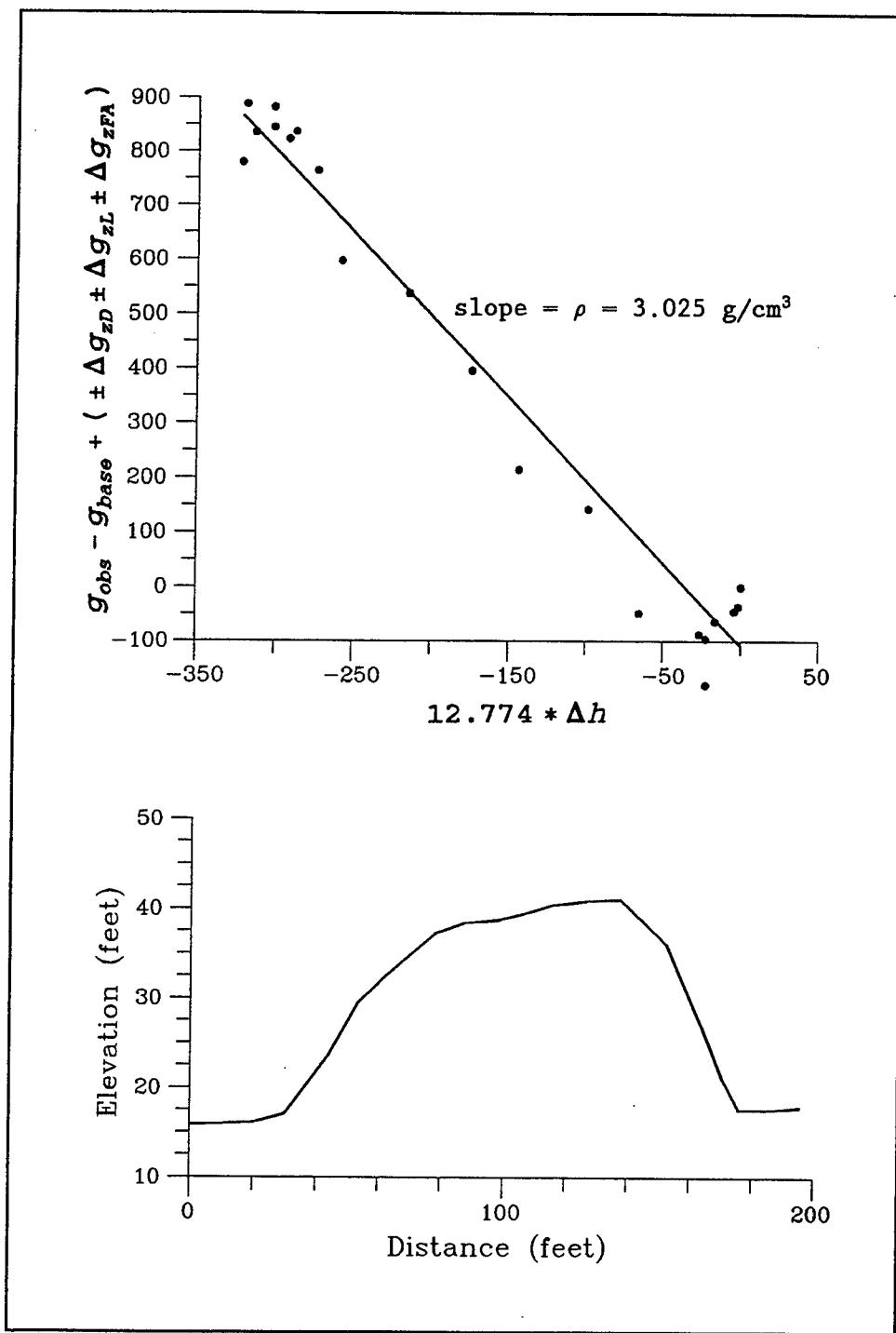


Figure 8. Application of Parasnis' method for computing material density



Figure 9. Pile No. 2

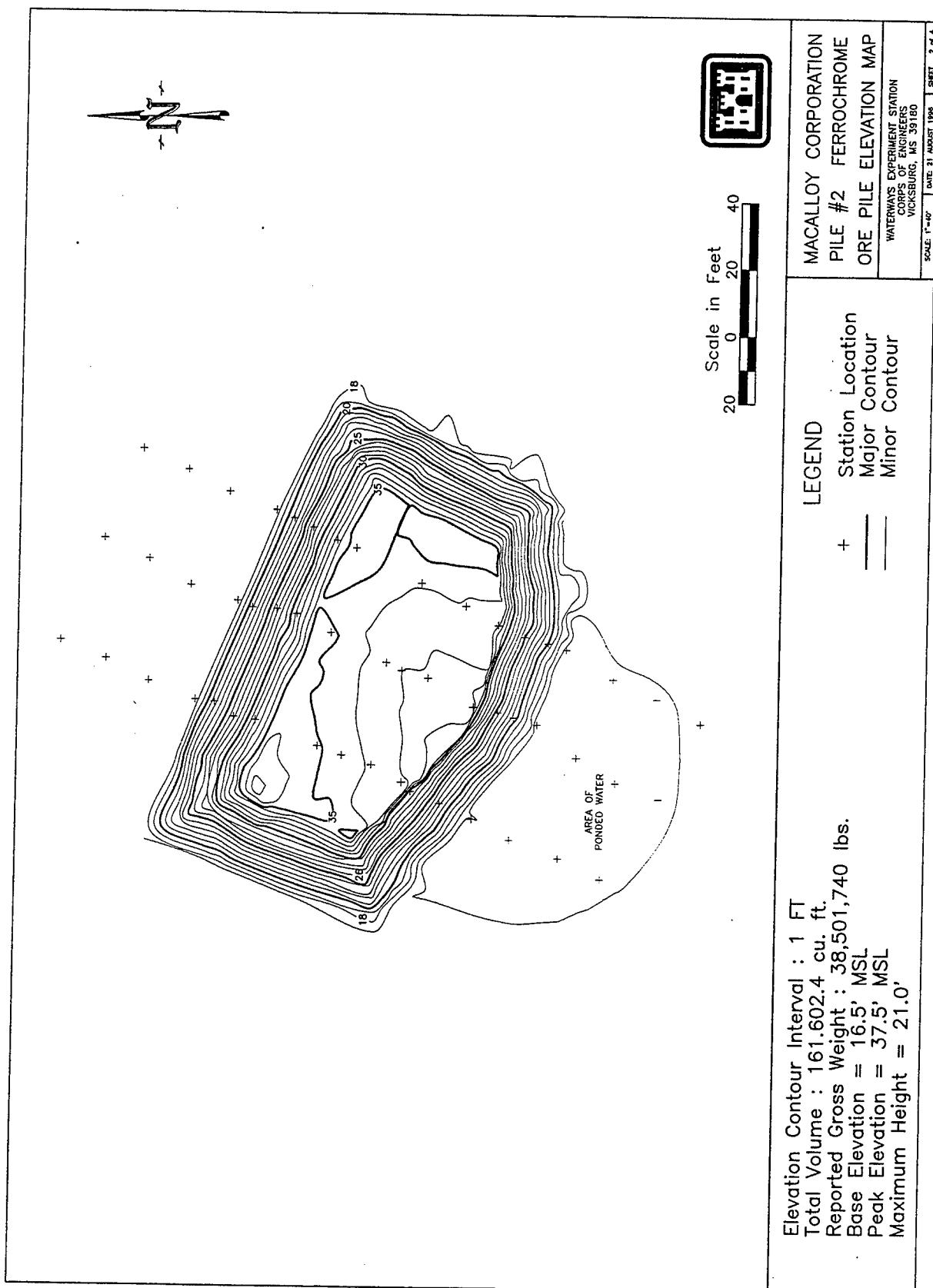


Figure 10. Elevation contour map of Pile No. 2



Figure 11. View of southwest corner of Pile No. 4

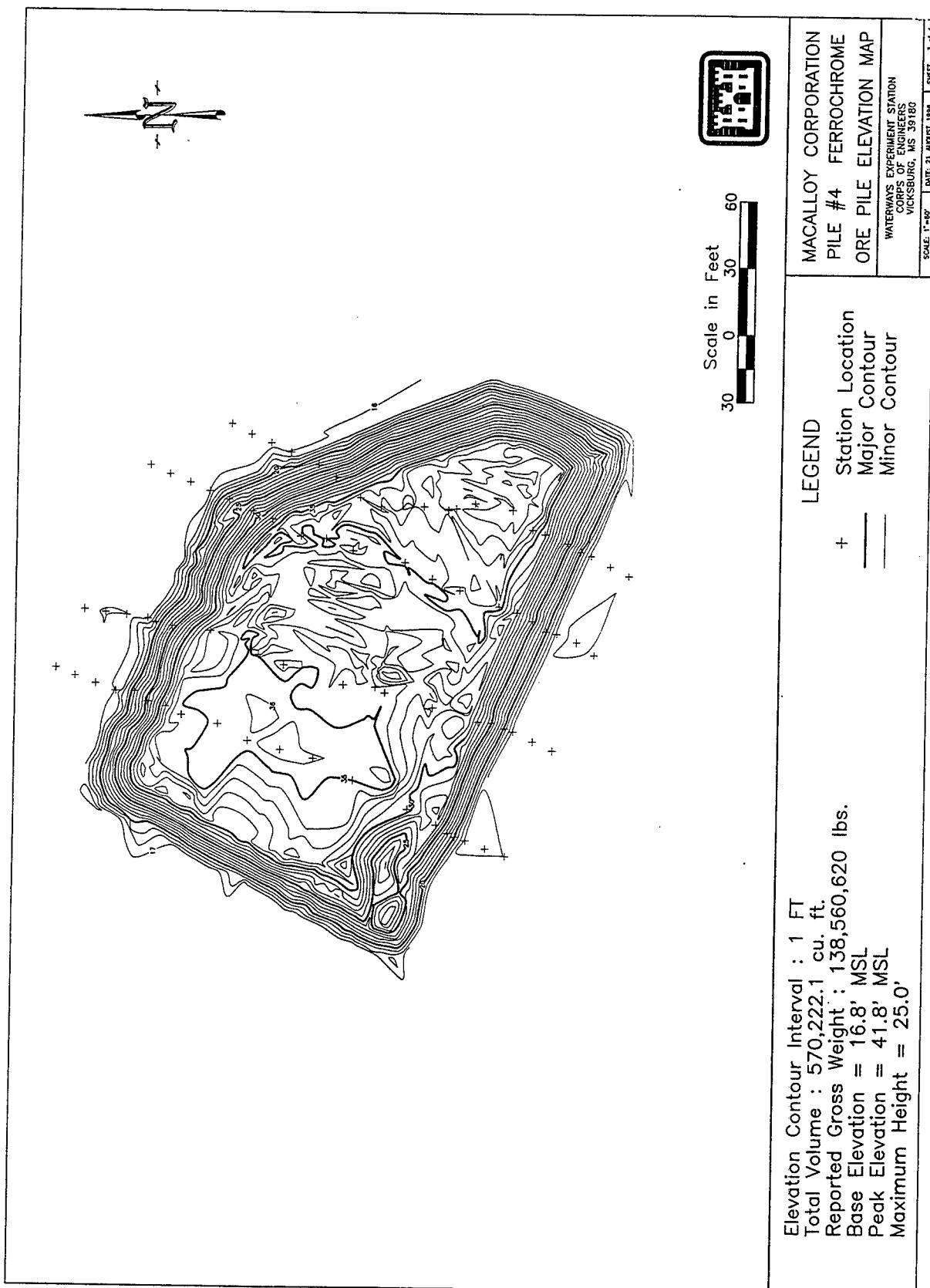


Figure 12. Elevation contour map of Pile No. 4

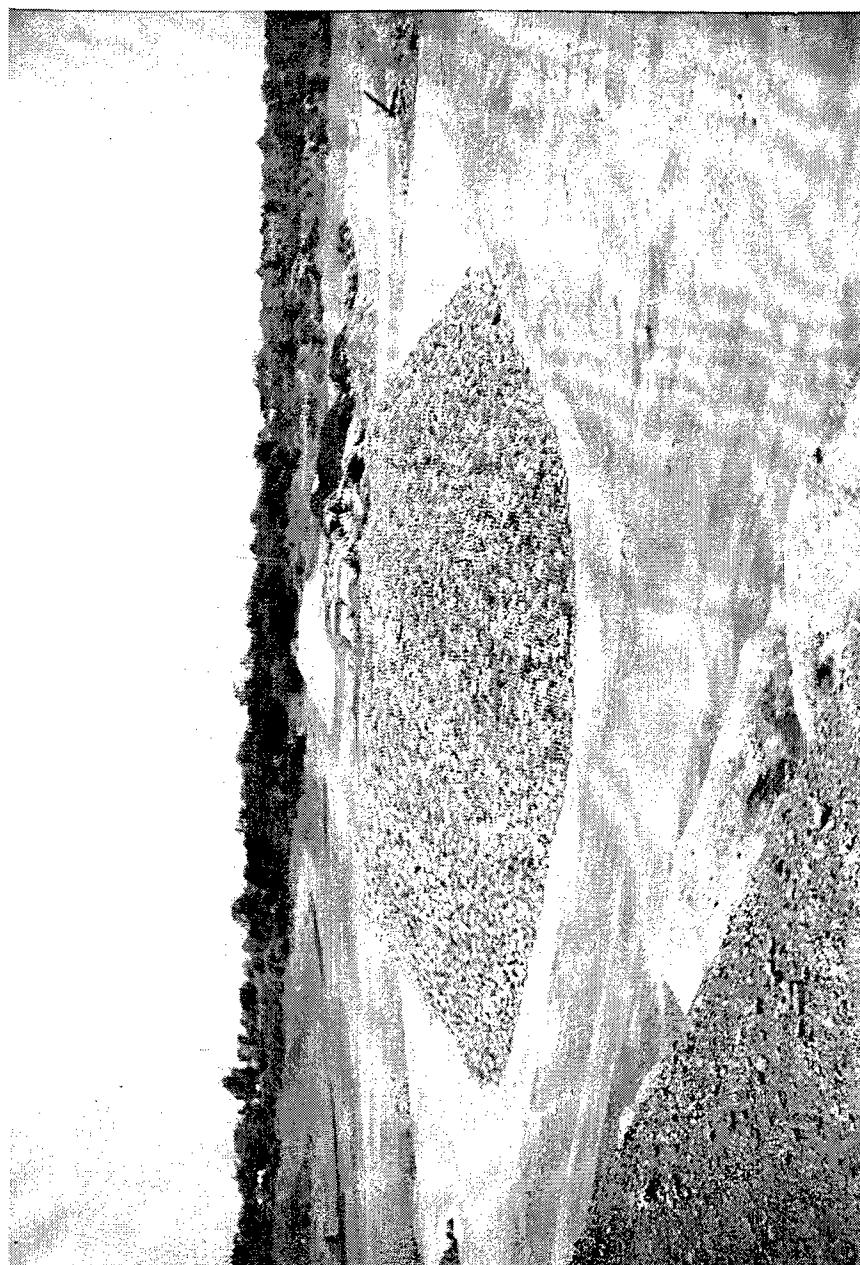


Figure 13. Pile No. 6

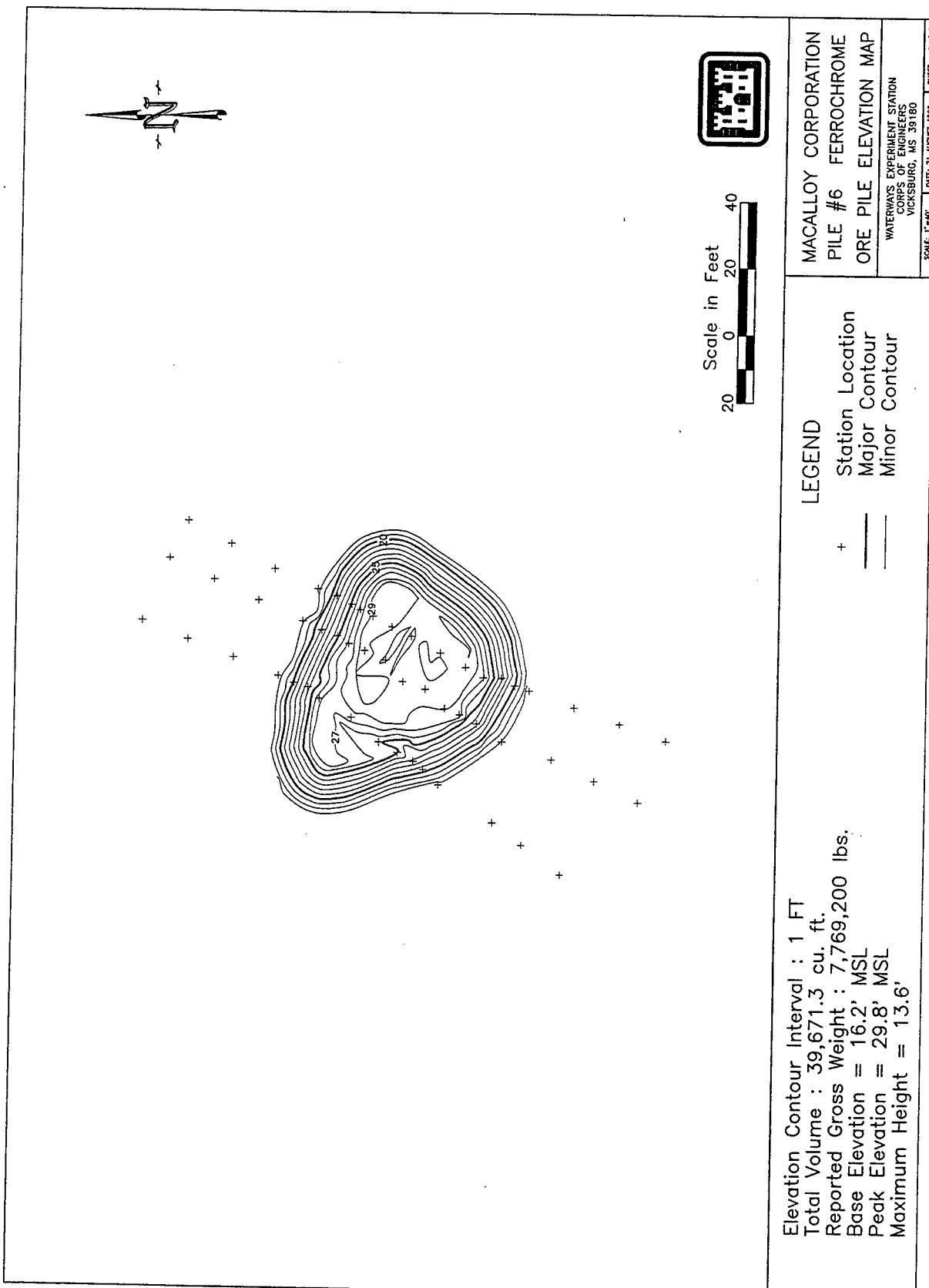


Figure 14. Elevation contour map of Pile No. 6

Table 1
Reported Descriptions of Ore Stockpiles¹

Pile Number	Length, ft	Width, ft	Height, ft	Reported Gross Weight, lb	Material Description
2	150	154	19	38,501,740	Ferrochrome, High Carbon, Domestic
4	270	175	22	138,560,620	Ferrochrome, High Carbon, Domestic
6	85	70	11	7,769,200	Ferrochrome, High Carbon, Domestic

¹ As provided by DNSC.

Table 2
Computed Volume, Material Density, and Weight of Ore Stockpiles

Pile Number	Average Volume, ft ³	Average Density, g/cm ³	Average Density, lb/ft ³	Average Calculated Weight, lb
2	161,602.4	3.683	229.90	37,155,999.4
4	570,222.1	3.775	235.64	134,381,790.4
6	39,671.3	3.085	192.57	7,640,310.7

Table 3
Comparison of Reported and Computed Ore Pile Weights

Pile Number	Reported Gross Weight, lb	Average Calculated Weight, lb	Standard Deviation of Calculated Weight, lb	Percent Difference ¹
2	38,501,740	37,155,999.4	2,259,827.2	-3.50
4	138,560,620	134,381,790.4	7,582,336.8	-3.01
6	7,769,200	7,640,310.7	170,885.4	-1.66

¹ Percent difference computed with respect to the reported gross weight provided by DNSC.

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